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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 453

WELDING IN AIRPLANE CONSTRUCTION

By A. Rechtlich and M. Schrenk

From "Jahrbuch 1927 der Deutsche Versuchsanstalt für Luftfahrt"

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Washington
February, 1928

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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WELDING IN AIRPLANE CONSTRUCTION.*

By A. Rechtlich and M. Schrenk.

The process of welding was employed to some extent even in the early years of airplane construction. Though the object of much distrust and the cause of many accidents due to faulty workmanship, it has nevertheless survived and won a place for itself among the methods of joining airplane parts.

The distrust, which even now is often manifested toward it, is not entirely unfounded. It results from the fact that the working of steel through fusing, as a metallurgical process, is not well understood by most mechanics and that no simple method has yet been discovered for determining the excellence of a weld, without its destruction or impairment.

The obvious advantages of welding are: a simple union of the parts, especially of tubes without increase of weight; construction of complex joints without great difficulty; quick and economical assembling and low cost of working plant. The extensive use, the important advantages and the uncertain results of welding led the D.V.L. ("Deutsche Versuchsanstalt für Luftfahrt") to undertake a thorough investigation of the problems connected with it. The present article attempts to explain the principles

*Das Schweißen im Flugzeugbau" from the 1927 Yearbook of the German Experimental Institute for Aviation ("Deutsche Versuchsanstalt für Luftfahrt"), pp. 76-82.

for the production of a perfect weld and to throw light on the unexplained problems. Moreover, it is intended to elucidate the possibilities of testing the strength and reliability of welded parts. It is based entirely on published data and practical experience and hence does not claim to present anything absolutely new. It provides the basis, however, for further research until the whole subject is better understood.

Part I. The Method Employed.

Hitherto the process of welding with acetylene and oxygen has been almost exclusively employed in airplane construction. This method is the most economical one for small cross sections, such as occur in the framework of airplanes. Moreover, a weld made with the acetylene-oxygen flame is stronger than an electric weld. The electric arc is too hot for cross sections of less than 3 mm (0.12 in.) thickness. For this reason we will first consider acetylene welding. The following items are involved in the production of a perfect weld, namely, the gases, tools, flame, material, welding wire, welder, and welding process.

Oxygen supports the combustion. Its chemical purity should be high, since this directly affects the temperature of the flame. According to recent researches, the most favorable purity of the oxygen is 97-98%. It has been demonstrated that the efficiency of the welding flame is not increased by a higher degree of purity of the oxygen. Below this point, the consumption of oxygen

increases and the temperature of the flame decreases about 2% for each decrease of 1% in the purity of the oxygen. Nitrogen is the principal impurity in the oxygen. It must be heated in the welding flame and thus acts as a useless heat consumer. It is also harmful if it gets into the weld..

Acetylene gas is a chemical compound, each molecule of which contains two atoms of carbon and two atoms of hydrogen, as expressed by the formula C_2H_2 . It should also be as free as possible from chemical and mechanical impurities (fine lime dust). The most important chemical impurities are hydrogen sulphide (H_2S) and water vapor (H_2O). The latter uselessly lowers the temperature of the welding flame, while sulphur and lime dust impair the strength of the weld. If the acetylene is generated at the place where it is to be used, the calcium carbide should conform to the standards of the German Acetylene Society. Acetylene can also be purchased in steel cylinders as so-called "dissolved acetylene." In the latter case, the acetylene gas, obtained from generators, is very carefully cleaned and dried, with the observation of special precautions, and forced into steel cylinders filled with a porous substance saturated with acetone. The liquid acetone dissolves the compressed acetylene gas at the rate of 24 liters of the gas for each liter of the liquid for each pressure increase of one atmosphere. The dissolved acetylene is more expensive than that taken directly from the generators, but is more convenient for some uses, when the containers are placed on movable trucks.

Mixtures of acetylene and air are explosive within the limits of 2.8 to 65% of acetylene. Mixtures of acetylene and oxygen are explosive within the limits of 2.8 to 95% of acetylene. These gases should therefore be mixed just before reaching the ignition place and their flow velocity should exceed the combustion speed of the mixture.

The oxygen delivered in steel cylinders is under a pressure of 150 atmospheres. This pressure gradually diminishes as the oxygen is used in welding. The working pressure of the oxygen is between 0.2 and 3 atm., according to the size of the burner, but must remain constant during the welding. In order to reduce the high and variable cylinder pressure to a uniform working pressure, a pressure-reduction valve is inserted between the container and the delivery pipe. Even the dissolved acetylene containers must be provided with such valves. Oxygen valves must not be handled with greasy hands or rags, for an explosion follows when oxygen comes in contact with grease.

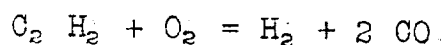
The burner is an instrument of precision. It must be light and easy to handle and must mix the gases well. The mouthpiece or nozzle must be exchangeable, and the gas pipes must be separately adjustable, in order to regulate the gas delivery for any change in the pressure or outlet cross section during the welding. Not all thicknesses of metal can be welded with the same burner. Thin sections are easily burned with a large burner while, conversely, thick sections cannot be thoroughly welded

with a small burner. The burner must therefore be selected according to the thickness of the metal to be welded.

In most burners the oxygen is delivered to the burner at a higher pressure than the acetylene, since the former must draw the latter along with it. There are also so-called "high-pressure" burners, in which both gases are delivered to the flame at about the same pressure.

A new burner with a pressure reduction valve has recently been put on the market. Its chief advantage is said to consist in the fact that no excess of oxygen can ever occur. This burner does not operate on the injector principle, but is supposed to supply automatically the proper quantities of both gases in the theoretical mixing ratio. It can be used wherever the acetylene is under a pressure of at least 0.5 atm. and is therefore especially suitable for using "dissolved acetylene." This burner, however, has not been in use long enough for final judgment to be pronounced on it.

The combustion of acetylene and oxygen takes place in two stages, of which the first stage is the most important. The first stage consists in the decomposition of acetylene and the formation of hydrogen and carbon monoxide, according to the formula



The second stage consists in the combustion of the substances formed in the first stage, thereby oxidizing them to carbon dioxide and water vapor, as represented by the formula

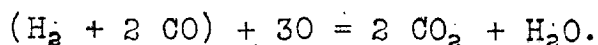


Fig. 1 shows the combustion zones in the acetylene-oxygen flame.

Zone 1 is luminous and contains the constituents of stage I, i.e., acetylene, oxygen, hydrogen, and carbon monoxide. At the end of zone 1 the chemical reaction is not yet complete. Zone 2 is not luminous. In it stage I of the combustion is completed and stage II begins.

Zone 2 is the most important zone for the welder as it is the working zone of the welding flame. It lies in front of the luminous cone and, with suitable adjustment of the flame, contains only reducing gases. These gases remove from the molten iron any oxygen it may contain and convert the iron oxide into metallic iron.

In zone 3 the combustion is completed with the aid of atmospheric oxygen. The mean maximum temperature of the flame is about $3000^{\circ}C$ ($5432^{\circ}F.$). The approximate temperatures of the flame are indicated in Fig. 2.

The most important thing for the working of the flame is its correct adjustment. Such is the case when the inner/^{cone} or core is sharply defined and clearly luminous (the hatched portion in the figures). If a luminous mantel is formed outside the inner cone and if it is less sharply defined, an excess of acetylene is indicated. Excess oxygen reduces the size of the luminous cone and gives it a bluish color. In either case the flame must be restored to its normal aspect by the proper adjustment of the deliv-

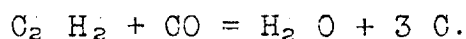
ery cocks on the burner. A correctly adjusted acetylene-oxygen flame has sufficient oxygen for complete combustion, since it also receives oxygen from the air (See formula for stage II). Hence, if there is an excess of oxygen from the cylinder, it will attack the metal and strongly oxidize it. An excess of oxygen is produced, however, only when the burner is overheated during the work, whereby the opening, from which the mixture flows, is enlarged and the counterpressure in the mixing chamber of the burner is increased. The counterpressure increase has but little effect on the quantity of oxygen, delivered at high pressure, but does retard the flow of the acetylene, which is under a lower pressure. Thus less acetylene is delivered and an oxygen excess is formed. Hence it is advisable to cool the burner frequently during protracted welding operations.

With excess oxygen the material oxidizes, forming oxide envelopes about the grains. This renders the metal porous and greatly impairs its strength. Since these oxide envelopes persist, even when the grains are disintegrated by subsequent heating, such an oxidized weld cannot be restored.

If the inner cone is allowed to act directly on the molten iron, the free oxygen can combine with the iron and likewise destroy the weld. A similar result may be produced, if the outer portion of the flame is allowed to act on the molten iron, since this portion contains free water vapor which, on contact with the molten iron, may be decomposed into oxygen and hydrogen, where-

upon the oxygen combines with the iron. These facts indicate the importance of the correct management of the flame.

In welding steel, excess oxygen is evidenced by the rapid formation of oxide (foaming) and by the star-shaped sparks thrown off. With a properly made weld, these sparks are spherical. Excess acetylene causes a hardening of the weld, due to the carbonization of the iron by the free carbon in the flame, probably liberated according to the formula



The best chemical composition of the material to be welded, as also of the welding wire, has not yet been definitely established. In this field much work must yet be done before final judgment can be pronounced. Hitherto it has been possible to make perfect welds only with steel containing very little carbon. This class includes the so-called "doubly refined" sheet steel which has a mean tensile strength of about 36 kg/mm² (51,200 lb./sq.in.) and an elongation of about 25%. Its carbon content lies between 0.06 and 0.13%. In many cases the material cannot be chemically analyzed, since steel analyses are very expensive and time-consuming and the proper equipment is not generally available. In such cases, therefore, only the tensile strength and elongation are determined.

The weldability of the material must also be tested. It was found that steel sheets which withstand the double-folding test, have perfect weldability. The double-folding test consists in

folding a piece of sheet steel, 180° each time, about two straight lines perpendicular to one another. The sheet must show no cracks after being thus folded. This test can be made with sheets up to 3 mm (0.12 in.) in thickness. These sheets also give good results with the Erichsen test.

The fitness of the material for blow-pipe welding has been thoroughly investigated by Dr. C. Diegel. The results of his investigations will be given in what follows. We will first consider briefly, however, the effect of sulphur, phosphorus, manganese, and silicon.

Iron with a sulphur content of only 0.03% disintegrates when worked at red heat (hot brittleness). Care must therefore be taken to free the acetylene gas of all hydrogen sulphide. If the sulphur content is less than that which produces the "hot brittleness," the strength characteristics of the iron are not directly affected. The harmful effect of sulphur can be diminished by the admixture of manganese. If manganese is added to iron which contains sulphur, a portion of the iron sulphide is converted into manganese sulphide, whose presence is not so harmful ($\text{Fe S} + \text{Mn} = \text{Fe} + \text{Mn S}$). The manganese sulphide goes into the slag and can be easily removed along with the latter.

Phosphorus is feared, because it produces "cold brittleness," i.e. brittleness of ordinary temperatures. This property is produced by a phosphorus content of only 0.05%.

More than 0.03% of silicon is also harmful because it com-

reacts with oxygen to form silicon dioxide ($2 \text{ Fe O} + \text{Si} = 2 \text{ Fe} + \text{Si O}_2$), which penetrates the metal in a finely divided form and makes it brittle ("burnt brittleness").

Diegel's investigations led to the following conclusions:

1. A high carbon content impairs the weldability of sheet steel. The cold-bending test showed that a carbon content of 0.3 and 0.31% produced unsatisfactory welds. A simultaneously higher manganese content of the sheet steel seemed to make but little improvement. Up to 0.15% the carbon content does not seem to affect the weldability. A content of only 0.06 - 0.12% is preferable, however.

2. The silicon content of sheet steel should be kept below 0.02%.

3. A manganese content of 0.4%, which is striven for in steel works in order to prevent hot brittleness, generally suffices for blow-pipe welding.

4. The phosphorus content must be very small. The tested sheet steel had 0.011-0.05%, within which limits no harmful effect of the phosphorus was noticeable. Sheet steel containing much phosphorus is cold-brittle and its welds have been found to break easily on further welding or from subsequent stresses or vibrations.

5. For high-grade welds the sulphur content should be less than 0.02%.

6. Up to 0.25% no harmful effect of nickel was observed. The maximum limit was not determined. Previous experiments had shown, however, that iron with 3-5% of nickel developed glass hardness.

7. Up to 0.21% the aluminum content was not found to be harmful. Here also, the maximum limit was not determined. It is desirable, however, for the aluminum content not to exceed 0.15%.

8. Up to 0.14% the presence of chromium did not impair the weldability of the iron.

In brief, Diegel's experiments indicated the following values, as the desirable composition of the steel for good blow-pipe welding:

C,	0.06-0.12, maximum 0.15%;		
Si,	less than 0.02%;		
Mu,	at least 0.4%;		
P,	not over 0.05%;		
S,	as low as possible, not over 0.03%;		
Ni,	up to 0.25%, maximum not determined;		
Al,	up to 0.15% ,	"	"
Cr,	up to 0.14%,	"	"

Recently, good welds have been obtained with a sheet steel which contains more carbon than doubly-refined sheet iron and hence a higher breaking strength. The chemical composition of this steel

is as follows:

C,	0.15-0.2, mean 0.18%;	
Mn,	0.6% maximum;	
Si,	0.13% " ;	
S,	up to 0.035 alone	} Not over 0.06% together.
P,	up to 0.035 " }	

This steel is delivered already annealed. It has a tensile strength of 40 kg/mm² (56,900 lb./sq.in.) and an elongation of 25% is striven for. Its tensile strength often reaches 45 kg/mm² (64,000 lb./sq.in.), its minimum elongation being 20%.

It is almost free from scale.

The parts made from this sheet steel must be thoroughly annealed after welding, the annealing temperature being between 900 and 925°C (1652-1697°F.). This eliminates the stresses developed during the welding, frees the metal from scale and makes the weld finer-grained. Samples of such annealed pieces show that the grain of the weld differs very little from that of the adjacent portions. The tensile strength of these pieces does not diminish after annealing and the elongation usually increases.

The steel tubing now used in airplane construction has, for the most part, a breaking strength of 45-50 kg/mm² (64,000-71,118 lb./sq.in.) with an elongation of 6-9% as drawn and 38-45 kg/mm² (54,050-64,000 lb./sq.in.) with 20-28% elongation as delivered. Good welds were obtained with tubes of the following composition:

C,	0.18 to	0.20%
Mn,	not over	0.60%
Si,	" "	1.00%
P,	alone,	0.035%
S,	"	0.035%
P and S together,		0.06%

In America weldable steel tubes are held in high regard. T. J. Johnson, Chief of Materials Section, Army Air Service, states that,* for fuselage construction, two types of steel tubing are used: first, carbon content 0.2-0.3%, tensile strength not less than 55,000 lb./sq.in., yield point 36,000 lb./sq.in.; second, a chromium-molybdenum steel with minimum tensile strength of 95,000 lb./sq.in., a yield point of 60,000 lb./sq.in., and the following chemical analysis: carbon 0.25-0.35%, manganese 0.4-0.6%, chromium 0.8-1.1%, molybdenum 0.5-0.25%. The chromium-molybdenum steel is used where high stresses are encountered, because welding causes practically no reduction in the strength of this alloy. In welding both types of tubing, a low-carbon welding rod, containing 0.08% carbon, 0.15-0.35% manganese, and not over 0.04% sulphur, has been found most satisfactory. A study of failures which had occurred in welded fuselages showed that improper welding or poor design was responsible in every case. ("Iron Trade Review," No. 25, 1925, p. 1346.)

*"Automotive Abstracts," Vol. III, 1925, p.371, abstract 4548.

F. T. Sisco and H. W. Boulton of the Air Service, McCook Field, state that* in welding chromium-molybdenum-steel seamless tubing and chromium-vanadium-steel sheet, chromium-molybdenum welding wire produces a weld which has a more desirable and uniform structure than low-carbon welding wire. In welding chromium-molybdenum-steel tubing to plain carbon-steel tubing, chromium-molybdenum-steel welding wire is not greatly superior and may even be inferior to low-carbon welding wire. Welded chromium-molybdenum-steel tubing has a soft area about $3/4$ in. from the weld, due to localized annealing at which spot failure in tension will occur unless the structure is made uniform by heat treatment. Heat treatment, consisting of quenching in water followed by tempering, greatly improves the structure of welded chromium-molybdenum-steel tubing and chromium-vanadium-steel sheet at and near the weld. The effect of heat treatment is not so important in its improvement of physical properties as in the refinement and equalization of the structure at the weld, although quenching, followed by a high tempering temperature, improves the ultimate strength and elongation sufficiently to make it advisable to heat-treat all welded chromium-molybdenum-steel tubes and chromium-vanadium-steel sheet, if possible. (Transactions of American Society for Steel Treating, November, 1925, p. 589.)

The importance of the progress made through these alloyed steels is greatly diminished if a subsequent heat-treatment is

*"Automotive Abstracts," Vol. III, 1925, p.389, abstract 4641.

necessary. With large working pieces, this can consist only in annealing in the free flame, which must be regarded, however, as an unreliable process.

It has been found that the quality of a weld depends even more on the properties of the welding wire than on the nature of the sheet steel to be welded. The quality of the welding wire depends on its chemical composition and on the manner of its production. It has been found that welding wires, which are objectionless as regards their chemical analysis, do not always produce good welds. It is very difficult to determine the reasons for this behavior. The fitness of the wire must therefore be determined by an actual welding test. First, however, we will consider its chemical composition. Diegel's experiments led to the following conclusions:

1. The most advantageous carbon content is 0.03-0.06%, the maximum limit being 0.1%;
2. Silicon should be eliminated as far as possible;
3. Manganese can more or less mitigate the harmful effect of sulphur;
4. In some cases no harm resulted from a phosphorus content of 0.07%;
5. The sulphur content must be kept as low as possible, as its harmful effect is not always eliminated by a high manganese content;
6. Very small quantities of nickel and chromium do no harm;

7. Aluminum is not harmful up to 0.07%. It is harmful, however, in greater quantities, due to the formation of aluminum film in welding.

According to the above conclusions, it may be said that a welding wire made from charcoal puddled steel or electrolytic steel, with a low percentage of foreign substances, is very suitable, with about the following composition:

C,	0.03 - 0.10%
Si,	0.00 - 0.03%
Mn, at least	0.35 - 0.50%
P,	0.00 - 0.05%
S, at most	0.02%
Al,	0.00 - 0.04%

These results show that a welding wire is likely to be more suitable in proportion to the purity of the iron, especially as regards sulphur.

As regards the properties of the welding wire, we will also quote from the specifications of the "Schweisstechnische Versuchsanstalt der Reichsbahn" (Government Railway Welding Laboratory) in Wittenberg.

"The welding wire, annealed or not annealed according to requirements, must have a uniform circular cross section and a smooth, flawless surface, free from rust and oil. The wire must be flexible, free from slate, and have a uniform grain."

The best results were obtained with welding wire of the following composition:

C, not over	0.10%
Mn, about	0.50%
Si,	traces
P, less than	0.04%
S, " "	0.03%

These values are now included in the specification.

Analysis alone does not suffice, however, for determining the excellence of the welding wire. This must be confirmed by an actual welding test. The wire is tested by drawing a weld "caterpillar" on a steel sheet. The wire must flow smoothly and spray but slightly. The flow and spraying of the wire can be best judged, when it is held in the direction of the flame in the zone of the weld and then allowed to melt off in drops. Of course the flame must be correctly adjusted and the wire must not be held in the core of the flame where there is still free oxygen. Even a good wire will spray vigorously in an excess of oxygen.

The mechanical excellence of the welding wire is determined by a cold-bending test. The sample must be capable of being bent about a cylinder having twice the diameter of the sheet steel at least 120° without cracking, whereby the weld zone must lie in the vertex of the angle of bend. It is worthy of note that the tensile test is entirely eliminated.

Because of the unforeseeable results of a poor weld in airplane construction, it is obvious that only specially skillful and careful welders should be employed. The welding of thin sheets and thin-walled tubes is very difficult and requires especially skillful workmen. Not every welder can do good work of this kind. A welder who is accustomed to weld only thick metal is liable to burn thin metal, while, in the contrary case, there is danger of the weld not being good all the way through. The work must be divided according to the ability of the individual workmen. This makes it necessary to know the ability of each welder. Only thus can there be perfect confidence in the proper execution of the welds. The welder must understand how much depends on the excellence of his work and must not lose his composure while working, especially in welding thin metal. He must be able to judge the heat expansions and the consequent contraction of the parts.

Not sufficient attention has hitherto been given to the training of welders and it has not been systematic enough. This was probably due to the fact that only a relatively small number of superintendents had themselves received any systematic instruction in welding. Many poor welds are doubtless due to these conditions. The welder learned mostly from his fellow workmen. He received only a purely practical training and had to make out the best he could with it. More attention has recently been given to the training of welders. Welding courses for engineers and work-

men are given in many places, though there is still much lack of suitable equipment for this purpose.

Since a faulty execution of the weld is often very difficult to discover after its completion, some degree of professional pride must be expected of the welder which will prevent him from turning in poor work or suffering his fellow workmen to do so. School training and making a special vocation of welding will tend to develop this professional pride, without which the task of the superintendent or inspector will always be a difficult one. When there is a large enough number of skilled welders available, confidence in the reliability of welded joints will automatically increase.

Welding is the fusing together of two pieces. For a satisfactory weld it is therefore essential that the joint or seam should be welded clear through. For this purpose, it is important for the material to be correctly fused before the welding wire is added. If metal parts of unequal thickness are to be welded, the thicker part must receive a preliminary heating, so that the two parts will fuse simultaneously. Ferrosoferric oxide ($\text{Fe}_3 \text{O}_4$) is formed on the iron at a low red heat and forms very rapidly on the surface of the fused metal. Its melting point is below that of steel. Hence, if steel is heated with the welding flame, the heated surface is covered with an oxide film at a certain temperature. This oxide fuses on further heating, while the steel itself remains unfused. If the heating is

continued till the steel fuses, it can be easily distinguished from the fused oxide, because the latter is difficultly liquefiable and is not so brilliant. It is also easily recognizable when the oxide and when the metal begins to fuse. Beginners, however, are apt to overlook the fact that, when the metal begins to "sweat," it is at first only the oxide that has begun to fuse. The application of the welding wire to such a surface, which shows only superficial signs of fusing, produces a very poor union, since the strength of the oxide is very small. Such a weld is worthless.

With thin cross sections, a good union should be effected with only once welding, in order that the neighboring portions may be annealed as little as possible and that the weld itself may not be oxidized by the repeated action of the welding flame. Hence, unless necessary, the seams should not be rewelded, as is sometimes done to produce a better appearance.

Part II. Testing the Welds.

The development of the working tests of the welds has not kept pace with the rapid development of the welding process. In rivet, screw, and other unions the constructor knows, from calculation methods based on many experiments, what stresses the structural parts can be expected to withstand. He does not know, however, what stresses the welds can withstand. His knowledge of the calculation methods and strength values in such unions is inade-

quate. Moreover, it is important for him to know how the stresses are developed in welded unions and how the weld is best made from this viewpoint.

No method of testing has yet been devised for determining the strength of a weld without destroying it. There are various ways, however, of forming an idea of the suitability of the material and of the quality of the weld, as also of the allowable stresses for the welded joint, which answer very well, on the whole, for the safety of welds in airplane construction. The tests may be classified as follows:

1. Workshop tests;
2. Laboratory tests;
3. Testing the finished work.

Workshop tests are chiefly to determine the suitability of the materials and the reliability of the work. The bending test is the most important one. It has already been explained in Part I, as to how the bending or folding test demonstrates the suitability of the sheet metal for welding. A similar test of the welded piece shows the quality of the weld. Folding the piece at the weld shows the angle of bend at which a crack first appears. The piece must be so held (e.g., in a vise) that the bending occurs in the weld. The stress should not be applied by hammer blows but by a steadily acting force.

The samples for the bending test are taken from two plates welded together, from which the beginning and end of the welded

seam have been cut off. The "Schweisstechnische Versuchsanstalt der Reichsbahn" employs, for bending the samples, a simple machine having two rollers on which the sample is laid. It is bent by a vertical stamp with a semicircular edge and twice the thickness of the sample. With this machine a uniform bend is made and the process is easily followed. The welded samples should allow a bend of at least 120° without cracking.

Another kind of test is made by clamping the sample between two edges whose radius of rounding equals the thickness of the sample, and bending the sample 90° back and forth until the weld cracks. The tenacity or strength of the weld is indicated by the number of bendings or the sum of all the angles of bend. This test fulfills its purpose only when the weld is sufficiently flexible to be bent. If it is hard and rigid, the bend occurs in the adjacent metal which, in this case, is not being tested. The testing of the metal and of the welding wire by the welding test has been sufficiently described in Part I.

The composition of the material suitable for welding and of the welding wire has already been discussed in Part I. The chemical analysis constitutes a very good criterion for the weldability of a metal. Unfortunately, the equipment for such work is expensive and hence seldom found in the workshops. Moreover, it must be said that an analysis alone affords no absolute criterion since an important role is played by certain peculiarities in the methods of producing the steel, which are not shown by the analy-

sis. The analysis must therefore yield to the welding test in the workshop. These two tests, taken together, can give a very good idea of the suitability of the metal for welding.

Investigations of the grain give a good idea of the structure of the steel in and near the welding point. They are therefore well adapted for confirming the quality of the welding work. They easily show whether a weld is oxidized, or excessively carbonized, or poorly executed. It is advisable here, as in all investigations for determining the quality of the welding work, not to give the welder any opportunity to prepare a so-called "show piece."

The strength of the weld can be determined by a simple tensile test. If it is desired to determine the strength of the union, the weld is left unfinished, but if it is desired to determine the strength of the weld itself, the weld is worked down to the thickness of the sheet. The tensile strength is expressed in hundredths (%) of the strength of the unwelded piece, in order to have a criterion for the quality of the weld. However, no perfect result is thus obtained, since the grain of the sample adjacent to the weld is altered by the welding heat, so that the failure occurs sometimes in the weld and sometimes in the adjacent metal, but more often in the annealed transition zone between the two and hence at the point of maximum expansion or elongation. Consequently the elongation measurement is not of much avail, since it cannot be perfectly executed. The weld itself

generally has very little to do with the change in shape, but the successive zones near the welding point behave very differently.

In many cases the welds are not stressed statically but by blows. In such cases impact tests are the most appropriate. Experiments have shown that resistance to blows depends much more than the static resistance on the carefulness of the welder. These tests are very difficult and are liable to give erroneous results. Much experience is requisite, in order to obtain accurate results.

The most important and dangerous stresses for welded structures are alternating or oscillating stresses. Hence, endurance tests are very important, as in all machinery construction. We will only refer here to Schenk's testing machine, with electromagnetic motivation and 500 vibrations per second, soon to be exhibited in the Dahlem government material-testing station. No German tests of this kind with welds have yet been published.

The behavior of welded tube connections toward continued vibration stresses has been investigated by the Engineering Division of the American Air Service ("Mechanical Engineering," October, 1925). The welded tube is placed on bearings at both ends, loaded vertically and rotated about its axis. At every revolution of 360° the weld is subjected to alternating tensile and compressive stresses. Previous experiments gave for the weld a considerably lower strength than for an unwelded tube, the former being only about half the latter. The result of the test is just

as important as regards the breaking point. In the static tensile test the gas-welded tube generally broke at one side of the weld. In the vibration endurance test, on the contrary, it broke in the weld.

This phenomenon also occurred on the welded support of a D.V.L. ("Deutsche Versuchsanstalt für Luftfahrt") engine-testing bench. The single-cylinder engine produced very rapid vibrations. The breaks all occurred in the weld, while the adjacent annealed zones remained intact.

Breaking tests of the finished parts are very important, since it is otherwise impossible to determine the reliability of the weld. This test was instituted partly to determine the actual strength of a structural part and partly to test the excellence of the welding, which is greatly affected by the more or less complex form of the part. Unfortunately such tests are quite expensive, especially when they are made on large parts like the fuselage or the engine mountings. In such cases, some expense is saved by taking the structure apart and testing individual junction points.

In these tests, the breaking strength is measured, the break is examined with the naked eye, or under a lens, for the effects of slag and the formation of bubbles, and it is determined whether the weld was rightly made, or was overheated or burnt. Hereby the metallographic investigation of sections, as explained above, renders good service. In all these tests, no specially prepared

"show pieces" should be tested.

A poor weld is generally recognizable from its untidy appearance and the unevenness of the seam, but whether the weld is properly combined with the adjacent parts cannot always be determined, as likewise whether there are the effects of slag or of burning. The weld may be poor, while presenting a good appearance.

With thin sheets it is especially important to determine whether their thickness has not been diminished by the welding. This can be easily determined by inspection. With open parts, it is likewise easy to observe whether the seams are welded clear through. Such is not the case, however, with tubes or closed hollow objects where one cannot see inside. Here we must be able to rely on the good work of the welder. One could tell this by observing the weld as it is being made. This would not be practicable, however, and, besides, it might make the welder nervous.

The ball pressure test is impracticable in welds, due to the thinness of the pieces and the complexity of the structure. It is natural to seek a method whereby we can see inside the pieces to be welded. The Röntgen method seems to afford certain possibilities in this connection, but its use has hitherto been much too expensive and favorable only for even or at least simple experimental pieces. Other methods of testing the weld by electromagnets or acoustic figures have yet led to no useful result. For the present, therefore, the fact remains that the reliability of the weld cannot be directly determined. This is also true to

some extent of riveting, which furnishes satisfactory security only through the large number of rivets. A similar statement can be made of welded joints, provided care is taken to provide enough excess strength at the welding point, so that any slight defect in the weld can do no harm.

Conclusion.— The production of a perfect welded joint depends chiefly on the following points:

1. On the suitability of the structure for welding;
2. On the use of suitable material and welding wire;
3. On the knowledge and conscientiousness of the welder.

The last point involves the education of the welder and the cultivation of his professional pride. The first two points must continue to be the subject of intensive research, until the fundamental conditions are clearly understood.

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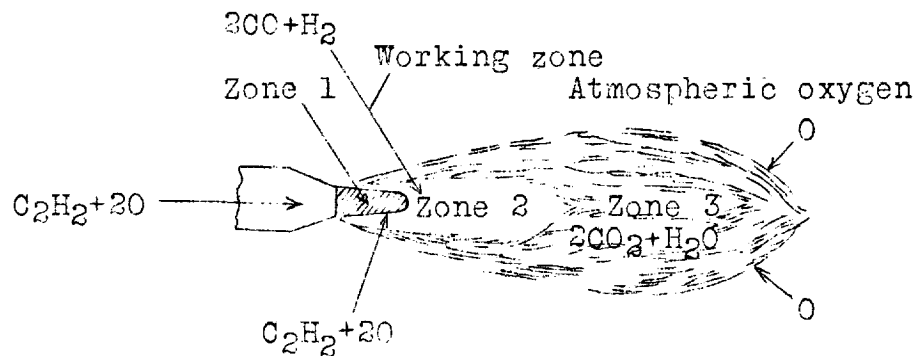


Fig. 1 Combustion zones in the acetylene-oxygen flame.

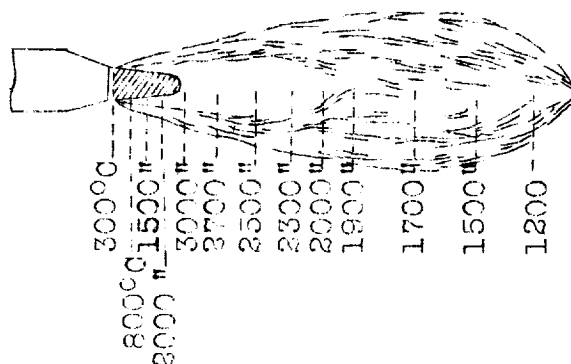


Fig. 2 Temperatures inside the acetylene-oxygen flame.